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SST Technology
Follow-On Program—Phase II
DEVELOPMENT AND EVALUATION OF THE ALUMINUM-BRAZED TITANIUM SYSTEM
Volume I—Program Summary

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FINAL REPORT

Task 1

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Prepared for

FEDERAL AVIATION ADMINISTRATION

Supersonic Transport Office
800 Independence Avenue, S.W.
Washington, D.C. 20590

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16. Abstract

Development and evaluation of aluminum-brazed titanium on the SST program was limited to specific applications and requirements of the prototype airplane. Subsequent to cancellation of the SST, the Department of Transportation (DOT) sponsored a two-phase technology follow-on program for aluminum-brazed titanium. Phase I documented the development status at termination of SST activities and authorized limited test work. Phase II authorized continued development of the braze system to optimize braze alloys, brazing processes, system scale-up, environmental testing, producibility, and structural verification. This report summarizes results of Phase II work.

Marked advancements were achieved in design and manufacturing criteria for aluminum-brazed titanium structure. System capabilities were successfully demonstrated by fabrication, test, and analysis of brazed hardware encompassing a wide range of configurations, structural load capacities, and test conditions. Results substantiate that aluminum-brazed titanium honeycomb sandwich structure is well suited for aircraft applications.

This braze system has been selected for use on the F-14, F-15, and B-1 airplanes. Control surface assemblies have been fabricated and certified for service evaluation on commercial subsonic aircraft. Areas of further development for increased system applications are defined.

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PREFACE

This is one of a series of final reports on aluminum-brazed titanium honeycomb sandwich technology submitted by the Boeing Commercial Airplane Company, Seattle, Washington, in fulfillment of Task I of Department of Transportation contract DOT-FA-72WA-2893, dated 1 February 1972.

To benefit utilization of technical data developed by the brazed titanium program, the final report is divided into eight volumes covering key technology areas and a summary of total program results. The eight volumes are issued under the master title, "Development and Evaluation of the Aluminum-Brazed Titanium System." Detailed volume breakdown is as follows:

	Report No.
Volume I–Program Summary	FAA-SS-73-5-1
Volume II–Process Research and Development	FAA-SS-73-5-2
Volume III–Scale-Up Technology	FAA-SS-73-5-3
Volume IV–Material Properties	FAA-SS-73-5-4
Volume V–Structural Verification	FAA-SS-73-5-5
Volume VI–Corrosion Resistance	FAA-SS-73-5-6
Volume VII–Producibility and Costs	FAA-SS-73-5-7
Volume VIII–Process Specification	FAA-SS-73-5-8

This report is Volume I of the series and was prepared by the Materials Technology organization of the Boeing Commercial Airplane Company.

The overall technical program and preparation of final reports was accomplished in cooperation with Mr. C. C. Troha, DOT Technical Monitor.

ACKNOWLEDGEMENTS

The success of this program can be attributed to the extensive efforts of a large number of people inside and outside of The Boeing Company. In particular, the authors wish to acknowledge the outstanding contribution of Mr. C. C. Troha, DOT Technical Monitor, for his able guidance and support throughout the program.

Special credit is due each of the investigating engineers who conducted the major technological inquiries: Messrs. R. R. Boyer, R. Q. Taylor, W. L. Cotton, D. V. Lindh, J. W. Fogleman, and R. Barton. Their technical expertise and dedication were indispensable to achieving the maximum understanding and technological advancement in their respective programs.

In addition, the program was dependent on the excellent support provided by the Operation Product Development and Technical Services organization headed by Mr. H. E. Buffum, the Structural Test organization headed by Mr. A. H. Kuhn, and the Boeing Material Technology laboratories headed by Mr. M. A. Disotell.

Lastly, we should like to acknowledge the significant technical, administrative and editorial support of Messrs. D. V. Lindh and W. L. Slosson.

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ABBREVIATIONS AND SYMBOLS

CS	core shear
EB	electron beam (welding)
EC	edgewise compression
EDI	electronic deflection indicator
EMF	electromotive force
FWC	flatwise compression
FWT	flatwise tension
GTA	gas tungsten arc (welding)
IML	inside mold line
NDT	nondestructive testing
OML	outside mold line
PA	plasma arc (welding)

Core configuration code:

SC 4-20 N M (Example)

- M = Machined both surfaces
  R = Rough–as fabricated
  M/R = Machined one side only
- N = Cell walls nonperforated
  P = Cell walls perforated
- Cell wall thickness in ten-thousandths of an inch, e.g., 20 = 0.0020 in.
- Cell size in sixteenths of an inch, e.g., 4 = 4/16 = 1/4 in.
- C = Corrugated cell wall
  S = Smooth cell wall
- S = Square cell shape
  H = Hexagonal cell shape

1.0 INTRODUCTION

Subsequent to the termination of the SST prototype, the Department of Transportation sponsored two technology follow-on contracts to first (Phase I), document major technological developments generated on the SST program; and second (Phase II), extend and broaden the development to provide the technological base for the widest achievable range of potential applications. One of the developments selected was aluminum-brazed titanium honeycomb sandwich structure.

The SST development of aluminum-brazed titanium honeycomb sandwich was essentially complete but limited in both development and evaluation to specific SST prototype requirements. This amounted to approximately 16,000 sq ft of moderately loaded wing and empennage skin structure, essentially flat and of uniform thickness, as illustrated in Figure 1-1. Evaluation was restricted to the 450°F environment of the SST. Specifically omitted from use on the SST prototype structure (for schedule and budgetary reasons) were the thick-skin (0.15 in.) high-load center wing box structure, and leading and trailing edge wedges and control surfaces. It was planned, however, to develop and use aluminum-brazed titanium for these structures on the production airplanes.

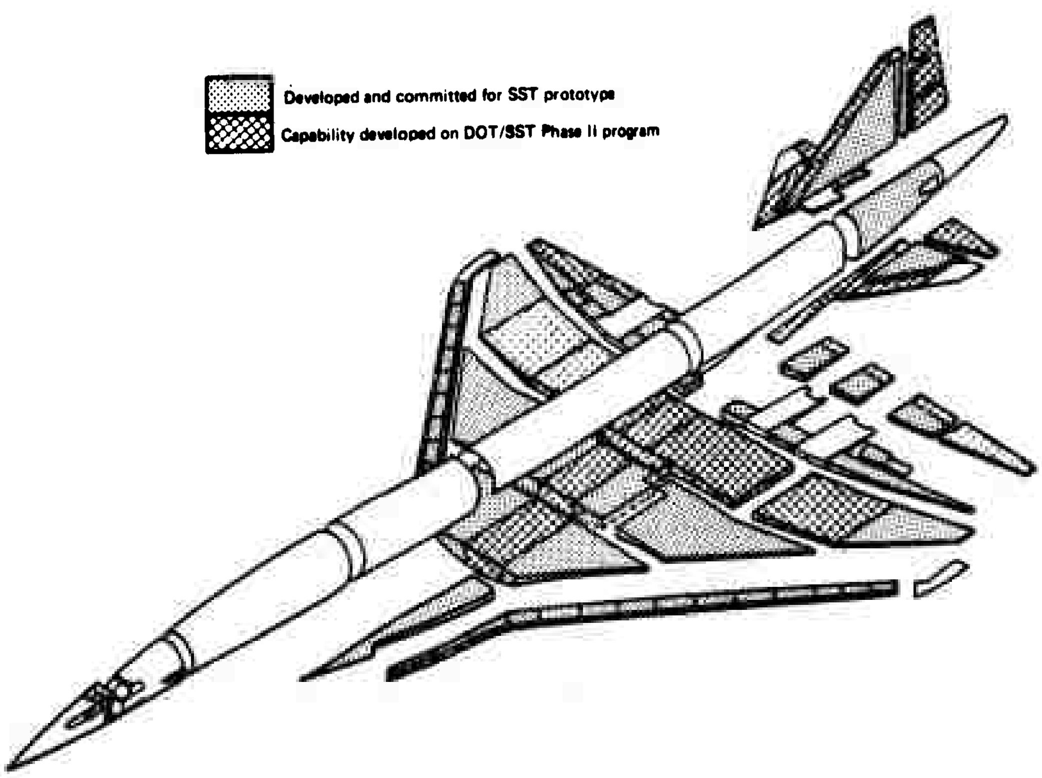


FIGURE 1-1.–APPLICATION OF ALUMINUM-BRAZED TITANIUM SANDWICH TO A SUPERSONIC TRANSPORT

The Phase I contract covered documentation of the SST development and implemented some long-term creep and environmental testing. This effort was documented in reports FAA-SS-72-03 and FAA-SS-72-14.

The Phase II contract covered a multi-faceted extended development and evaluation of the brazing system with four fundamental objectives:

1. Extend the development and evaluation of the aluminum-brazed titanium system to establish the broadest possible technological base for the widest variety of potential applications. To outline the maximum permissible service environment, this effort included the establishment of the process parameters and limitations for skin thickness, core configuration and depth, determination of mechanical properties, environmental stability, and corrosion resistance.

2. Demonstrate the production viability of the system by design and manufacture of critical structures representative of a high-load center wing box structure and a wedge-shape control surface.

3. Verify the structural adequacy of the system by component testing and flight service evaluation.

4. Study the producibility aspects of the system to delineate the most cost effective design criteria and manufacturing procedures.

Documentation of the results of this program has been assigned an overall report number, FAA-SS-73-5. The various development programs were grouped into major technological areas and documented in detail as individual dash-numbered reports:

Volume I–Program Summary — Report FAA-SS-73-5-1
A review of the overall program objectives, accomplishments, and conclusions.

Volume II–Process Research and Development — Report FAA-SS-73-5-2
Investigations into basic process parameters and techniques.

Volume III–Scale-Up Technology — Report FAA-SS-73-5-3
Fabrication techniques and procedures developed for full-scale aircraft components.

Volume IV–Material Properties — Report FAA-SS-73-5-4
Evaluation of basic mechanical and thermal properties for various core configurations and depths.

Volume V–Structural Verification — Report FAA-SS-73-5-5
Evaluation and analysis of structural components, including fatigue properties.

Volume VI–Corrosion Characteristics — Report FAA-SS-73-5-6
A study of the fundamental corrosion characteristics of the system and an extensive laboratory and field service corrosion test program.

Volume VII—Producibility and Costs | Report FAA-SS-73-5-7

A study of manufacturing methods and design requirements to establish basic parameters affecting cost effectiveness.

Volume VIII—Process Specification | Report FAA-SS-73-5-8

The basic process specification and engineering acceptance criteria used as the baseline control for Phase II program brazing.

Major combinations and permutations of the system were tested and evaluated, and three basic approaches were taken depending on the specific objective:

1. Variables were selected and test matrices designed to permit parametric analysis of the full range of characteristics.

2. Test parts were selected which would realistically represent production applications.

3. Specific problems (primarily production/process) were solved as they were identified during the development of processing techniques for the wide variety of parts produced.

This document presents first, an overall summary of the program accomplishments, followed by detail summaries of the major technological areas and a brief review of the status of the process specification. A glossary of uncommon terms, with an explanation of the core configuration code, is included.

A considerable portion of the work accomplished was a completion or extension of work conducted on the SST and Phase I programs. In order to achieve a more complete understanding of the total development of the aluminum-brazed titanium system, readers are directed also to previous reports: "Development of Aluminum-Brazed Titanium Honeycomb Sandwich Structure," FAA-SS-72-03; and "Creep and Corrosion Testing, Aluminum-Brazed Titanium Honeycomb Sandwich," FAA-SS-72-14.

2.0 OVERALL SUMMARY

The principal technological advances made on the program are shown in Table 2-1. The following paragraphs discuss salient accomplishments of the overall program.

- The selection of 3003 aluminum as the preferred alloy for brazing titanium was reconfirmed. The program also established the basic process parameters and mechanical properties for a wide variety of core configurations, ranging in density from 1.5 to 10 lb/cu ft and depths up to 3 in., including wedge structures.

- The system was shown to retain acceptable long-term mechanical properties up to 800 F. Short-term exposures up to 1000°F could be tolerated, depending on the stress level. The corrosion characteristics under laboratory and actual field service conditions were shown to be excellent, being essentially equivalent to 3003 aluminum. The natural passivation of the aluminum and titanium was shown to eliminate galvanic corrosion between the two metals.

- Scale-up under factory conditions demonstrated the reliability and versatility of the process. Brazements totalling 130 units were successfully made, including 2 complex simulated high-load wing panels capable of supporting end loads up to 30,000 lb/in., and 3 model 737 airplane flight spoilers. Of the latter parts, 2 are being evaluated in flight service on commercial airplanes.

- Concepts have been developed which demonstrate the feasibility of fabricating aluminum-brazed titanium sandwich with a thermal conductance approaching that of all-titanium welded or diffusion-bonded sandwich.

- The feasibility of assembling brazed components by welding was also demonstrated; stress-relieving parameters which would reduce residual welding stresses to an acceptable level without damaging the braze were identified.

- The structural integrity of the system has been verified by an extensive test program, including static and fatigue tests on structural components ranging from simple joints to the 737 flight spoiler and high-load panel.

- A study of the producibility aspects of the system identified nondestructive inspection and detail machining costs induced by design complexity as the principal cost elements. Minimum development efforts demonstrated the feasibility of a new inspection system based on an automated eddy current technique which could be significantly more efficient than current methods. A variety of panel joint configurations designed to minimize machining requirements was fabricated and tested; the results showed that the concepts were feasible with little or no loss in structural efficiency. The principal cost factors which should be considered by the designer have been delineated.

- The additional capabilities established on the Phase II program are illustrated in Figure 1-1.

TABLE 2-1.—ALUMINUM-BRAZED TITANIUM SYSTEM TECHNOLOGICAL PROGRESS

Key category	Specific technological progress	Status: SST Prototype (1970)	Status: DOT/SST Phases I & II (1974)
Process research and development	1 Maximum core depth	1.5 in.	3.0 in.
	2 Minimum core density	5 pcf	1.6 pcf
	3 Maximum braze angle	25°	360°
	4 Wedge-shaped sandwich	No	Yes
	5 Acoustic sandwich	No	Yes
	6 Faying-surface braze	No	Yes
	7 Post-braze weld assembly	No	Yes
	8 Minimum node permeability requirement	No	Yes
Scale-up technology	1 Maximum nominal skin thickness	.09 in.	.15 in.
	2 Panel end-load capability	18,000 lb/in.	30,000 lb/in.
	3 Flight hardware capability demonstrated	No	Yes
	4 Wedge-shaped structure	No	Yes
	5 Acoustic structure	No	Yes
	6 Faying-surface braze	No	Yes
	7 Net-brazed edge capability	No	Yes
Material properties	1 Core depth data	1 in.	1/4, 1, 2, 3 in.
	2 Core configuration data	SS 2-20, SC 4-20, SC 4-30	SS 2-20, SC 3-15, SC 3-20, SC 4-20, SC 4-30, SC 6-15, SC 8-20
	3 Evaluated temperature data	RT, 450°F	RT, 450°, 600°, 800°, 1000°F
	4 Minimum thermal conductivity	9 Btu-in./hr-sq ft-°F	2.5 Btu-in./hr-sq ft-°F
	5 Stress-rupture data	1000 hr @ 450° & 600°F	10,000 hr @ 450°, 600°, & 800°F
	6 Analysis of effect of brazing on fatigue	No	Yes
Structural verification	1 Compression panel design data verified	No	Yes
	2 Structurally efficient single-surface edge joint designs	No	Yes
	3 Acceptable constraints for access hole design	No	Yes
	4 Flight hardware certification	No	Yes
Corrosion resistance	1 Flight service evaluation	2 airplanes = 1 yr	21 airplanes up to 4 yrs
	2 Accelerated corrosion tests	3 months	18 months
	3 Galvanic corrosion	Indicated none occurs	Established none occurs
	4 Stress corrosion	Unknown	Established none occurs
	5 Protection for honeycomb fastener holes	Sealant filled	Not required
	6 Faying-surface braze	Not permitted	Permissable with restrictions
	7 Corrosion mechanisms established	No	Yes
	8 Inspection test methods established	No	Yes
	9 Engine exhaust tests	No	Yes
Producibility	1 Principal cost elements identified	No	Yes
	2 Cost effective alternatives identified	No	Yes

Further confirmation of the viability and integrity of the system has been its selection for a variety of structures on the F-14, F-15, and B-1 airplanes. In addition, the system has been selected for acoustic sandwich structures for the Boeing/NASA Refan program to develop new concepts for jet engine noise reduction.

3.0 DETAIL SUMMARIES

3.1 PROCESS RESEARCH AND DEVELOPMENT (REPORT FAA-SS-73-5-2)

This portion of the program covered a broad range of research and development to establish basic process parameters for structural concepts beyond those used on the SST prototype.

3.1.1 Braze Alloy Research

In the initial SST development, 3003 aluminum was selected from over 100 candidate braze alloys as having the best combination of properties (report FAA-SS-72-03). An undesirable characteristic of 3003 aluminum as a braze alloy is the extreme fluidity and flow exhibited at the high end of the braze temperature range. This factor does not seriously impair application, but a more sluggish braze alloy would potentially decrease panel weight and increase permissible panel depth.

During the last days of the SST program an experimental laminated Al-Al/Si braze alloy indicated much more restricted flow. An extensive effort to duplicate that result on the current program was unsuccessful. An investigation of a variety of new, experimental aluminum-base powder braze alloys showed none of potential interest. An extensive effort was also made to braze honeycomb sandwich with Ag-5Al-0.5Mn. No temperature cycle could be found which gave acceptable melting and flow.

As the silver alloy exhibits no technological advantage over 3003 aluminum and costs approximately 400 times as much, no further development or evaluation was attempted.

3.1.2 Beta-III Core

Beta-III (Ti-11.5Mo-6Zr-4.5Sn) titanium alloy is of interest for honeycomb core because of its reported excellent formability and high strength.

The core manufacturer reported severe problems in forming the foil and could not meet core shape requirements readily met with Ti-3Al-2.5V foil. This problem was traced to a cold-working operation after the last anneal.

The Beta-III core was readily brazable using the 3003 aluminum system. Braze alloy flow was restricted to the formation of face skin and node fillets, with no excessive flow over the cell walls. The flatwise tensile strength of the 1-in. core was slightly lower than Ti-3Al-2.5V and required 25% less braze alloy. Additional work would be required to achieve a complete understanding of brazing/property parameters.

3.1.3 Braze Alloy Quantity Requirements

Every core configuration and depth requires a different amount of braze alloy. The braze alloy requirements for a wide variety of core configurations and depths were established. Data from this activity were used to support other tasks in the program and to prepare parametric graphs covering the full range of potential usage for the system. Figure 3-1 indicates the range of requirements established.

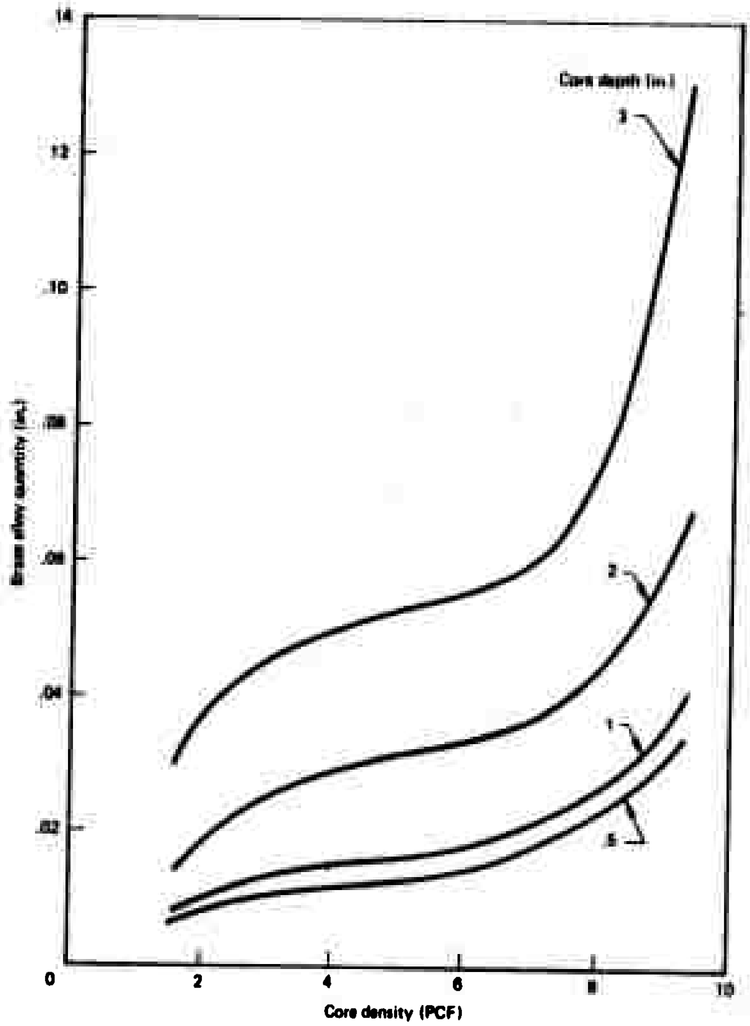


FIGURE 3-1.–BRAZE ALLOY REQUIREMENTS

3.1.4 Rotational Brazing

With conventional static brazing procedures, part curvature is limited to approximately 25° from horizontal by gravity flow of the braze alloy. To circumvent this problem, a device was fabricated to rotate the brazing retort during the braze cycle, Figure 3-2. Braze alloy migration was successfully eliminated at a speed of approximately 1.5 rpm, with a significant improvement in temperature stability. The technique was applied to cylindrical parts and could also be used for any shape, including deep flat panels.

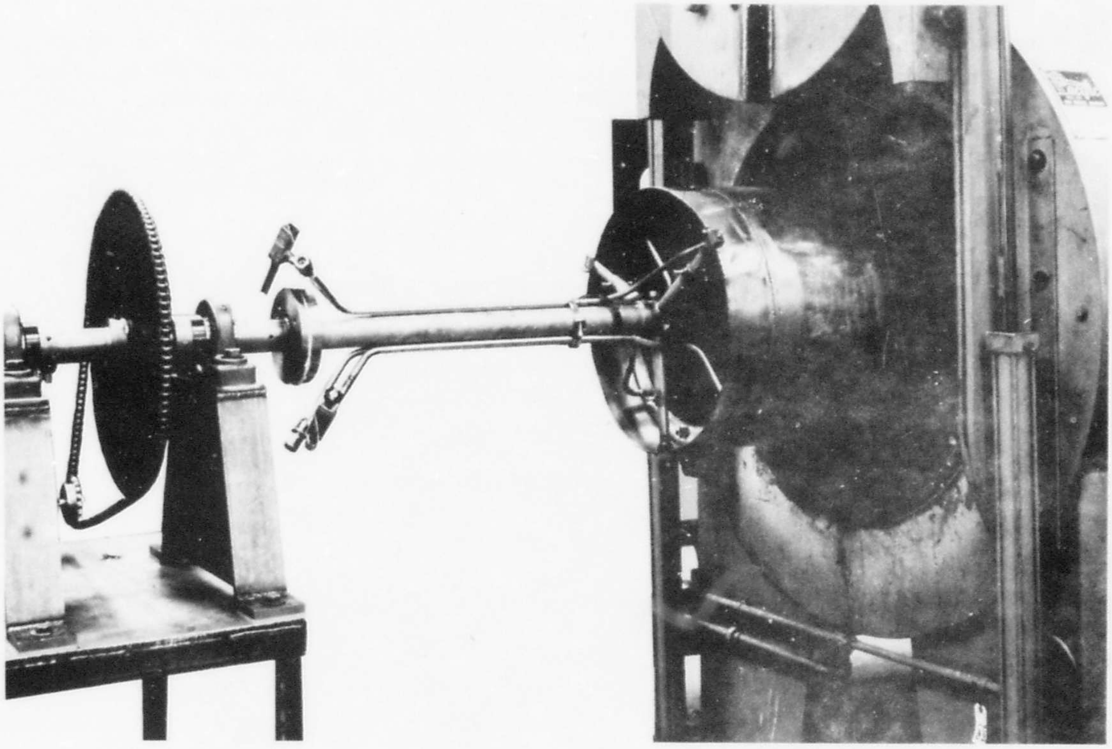


FIGURE 3-2.—ROTATIONAL BRAZING DEVICE

3.1.5 Cleaning

As stated in the past, the overriding critical factor for successful brazing is cleanliness. A troublesome splice line void problem encountered on some SST prototype panels was traced to inadequate cleaning of the core; less than optimum splicing between two pieces resulted in doubled cell walls and tight cell fragments. The problem was largely solved by using a pressure-lance cleaning method. However, a combination of a poorly made splice and less than optimum lance cleaning resulted in a splice line void on one panel. Ultrasonic cleaning was investigated in the laboratory and was shown to provide significantly improved cleaning.

3.1.6 Faying-Surface Braze Development

Faying-surface joints have been extensively used for brazed assemblies and are nearly mandatory for some design applications. Historically, this type of joint has had a high rejection rate with any brazing system. Faying-surface joints in general are not recommended; however, because of the importance of some design applications, considerable effort was made to identify critical process parameters and evaluate the utility of such joints. Parameters were established for producing acceptable faying-surface joints using certain design limitations and constraints.

Since a significant amount of aluminum is consumed in the formation of $TiAl_3$, it is necessary to control the minimum joint gap to assure sufficient residual metallic aluminum to transmit the load. On the other hand, large gaps increase the prevalence of voids. The optimum gap was established at 0.005 ± 0.001 in. The only identified procedure which could guarantee this control was pre-braze spot welding. This procedure was shown to provide the necessary control, and the braze reinforcement around the spot weld completely abrogated the stress concentration at that point. Figure 3-3 illustrates the braze reinforcement around a spot weld.

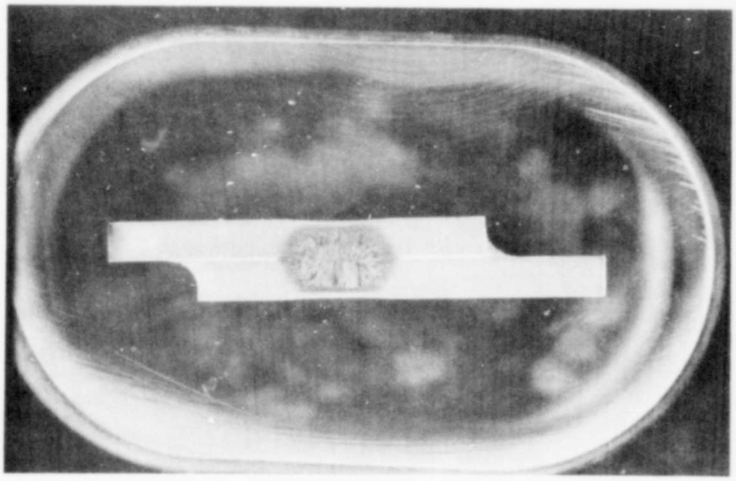


FIGURE 3-3.—BRAZE REINFORCEMENT AROUND SPOT WELD

3.1.7 Post-Braze Weld Development

Many potential design applications necessitate an extremely complex brazement if made in one piece. Greatly increased design versatility and production efficiency could be realized if brazed subassemblies could be welded together. With the aluminum brazing system the approach is restricted by two criteria:

- o All aluminum must be precluded from the fusion zone of the weld to prevent extreme embrittlement.

- o The welded assembly cannot be given a normal stress-relief as the 1250°F temperature would remelt the braze.

The requirements and procedures to preclude aluminum from the weld were established for GTA, PA, and EB welding. A partial stress-relief of 3 hours between 950 and 1000°F was shown to reduce residual stress to an acceptable limit (less than 30,000 psi). Neither welding nor the stress-relief caused significant damage to the braze. Figure 3-4 is a photograph of a sample weldment.

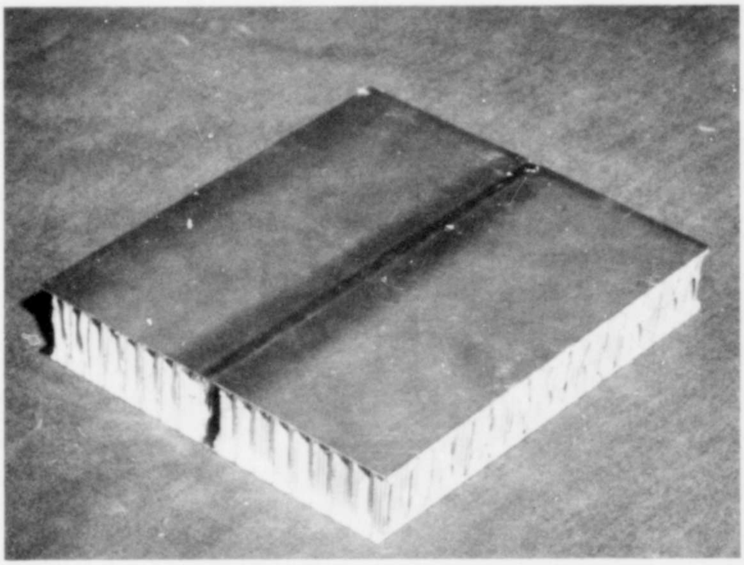


FIGURE 3-4.–POST-BRAZE WELDMENT

3.1.8 Low-Density Core Process Development

Honeycomb core with a density lower than approximately 5 lb/cu ft will crush under the 1 atmosphere clamp-up pressure produced by conventional retort brazing procedures. Since a full vacuum is mandatory in the brazing retort, a dual retort/vacuum system was fabricated to provide the necessary control over clamp-up pressure. This device was used successfully for both flat panels and wedges, with core densities as low as approximately 1.6 lb/cu ft.

3.1.9 Acoustic Sandwich Process Development

Acoustic honeycomb sandwich for jet engine noise suppression is a potentially large area of use for the brazing system. Two additional factors must be resolved for this application:

- Hole blockage in the perforated acoustic face sheet must be minimized and controlled.
- Parts with a curvature of at least 120°, and preferably 360°, must be made.

One-, two-, and four-layer flat panels were made successfully. Stop-off was required to control hole blockage for holes smaller than approximately 0.050 in. Single- and double-layer half-cylinders were successfully made using a device which rotated the retort during the braze cycle to prevent gravity-induced migration of the braze alloy.

Figure 3-5 is a photograph of a small segment of a curved double-layer sandwich. Since that time, 360° brazes have been successfully made on other programs.

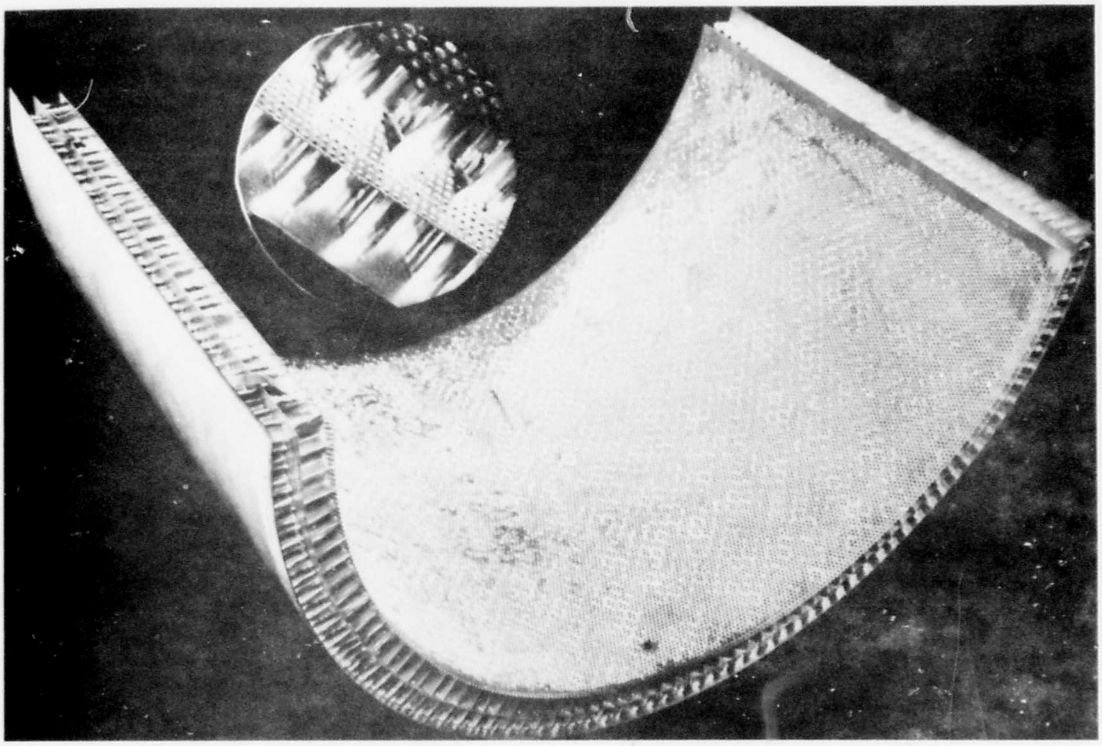


FIGURE 3-5.—DOUBLE-LAYER ACOUSTIC SANDWICH

3.1.10 Node Ventilated Core

It was established during the SST development that some minimum gas permeability through the honeycomb core nodes was required for an acceptable braze. To further delineate the requirement and establish a positive method of assuring the necessary permeability, core was fabricated with a small notch (dimple) perpendicular to the node. The notches were formed simultaneously with the rest of the core-forming operation. The procedure was both simple and effective. Figure 3-6 is an enlarged photograph of a node notch.

3.1.11 Uncontrollable Exothermic Reaction

The $Ti + 3Al \longrightarrow TiAl_3$ reaction is exothermic. Further, it was established during the SST development that certain contaminants, particularly lead, could accelerate the formation of $TiAl_3$ to the degree that all available aluminum would be consumed. Two isolated incidents where complete conversion to $TiAl_3$ occurred were encountered on this program. The first occurred on a brazement employing 3-in.-deep SS 2-20 core. The second occurred with 5-in.-deep SC 4-20 core. Minute amounts of lead and gallium were found in both cases.

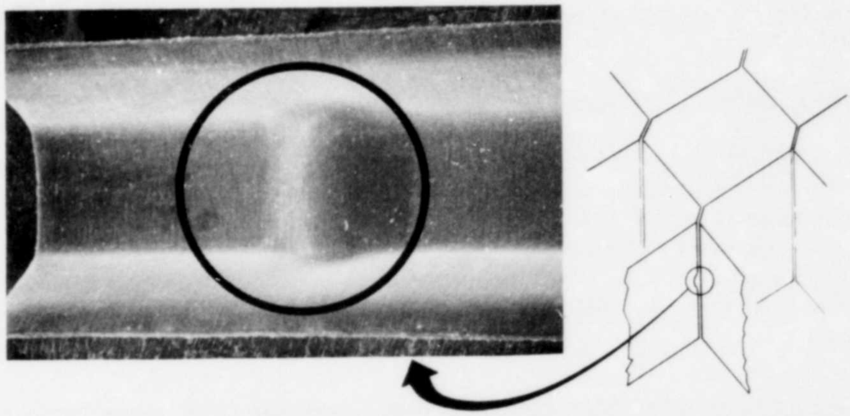


FIGURE 3-6.—DIMPLE IN CORE NODE FOR VENTILATION

A theoretical thermodynamic analysis of the systems indicated that with certain combinations of variables (number of core nodes, cell wall surface area, depth of sandwich, amount and distribution of braze alloy, and cooling capability of the heat source), the heat generated by the $TiAl_3$ formation is sufficient to maintain or accelerate the exothermic reaction. The presence of a "catalytic" contaminant would worsen the phenomenon. The phenomenon is not expected to be a problem other than for exceptionally deep sandwich (over 3 in.) and heat sources with poor cooling capability.

3.2 SCALE-UP TECHNOLOGY (REPORT FAA-SS-73-5-3)

The basic objective of this effort was to fabricate three types of structure:

1. Boeing Model 737 airplane flight spoilers for laboratory and airline flight service evaluation.

2. Heavy, thick-skin simulated wing skins capable of supporting end loads up to 30,000 lb/in.

3. A relatively large quantity and area of simple flat panels necessary for the parametric evaluation of mechanical properties.

There are two basic approaches to generating the necessary part size: (1) the part may be brazed net to final dimension, or (2) the part may be brazed oversize and trimmed to size after brazing. Where possible, the former approach is preferable because the latter inevitably results in partially-opened honeycomb cells which are extremely difficult to coat effectively with protective finish. In addition to the basic objectives, a secondary objective was to develop procedures for obtaining acceptable net-brazed part quality. This latter objective was achieved by controlling minute amounts of contaminants which tend to concentrate on the periphery of the part and inhibit braze alloy flow and wetting. Processing problems encountered and procedures developed in fulfillment of these objectives established both general criteria applicable to all brazing and specific criteria applicable to the individual parts.

3.2.1 Boeing Model 737 Airplane Flight Spoilers

Model 737 flight spoilers were selected for the flight service test article. This part was representative of the difficulties which would be encountered in fabrication of wedges and raised problems in introducing point loads into honeycomb sandwich structure. Three spoiler assemblies were successfully fabricated. One was static and fatigue tested, meeting all design requirements. The other two have been installed on commercial Model 737 aircraft (All Nippon Airways) for field service evaluation. Figure 3-7 is a photograph of the finished part.

FIGURE 3-7.—737 FLIGHT SPOILER

3.2.2 High-Load Panel

A second basic objective was to establish manufacturing procedures for heavy, thick-skin honeycomb sandwich structure capable of supporting end loads up to 30,000 lb/in. Such a panel would be representative of the skins on a main wing box. The fundamental problem to be resolved was achieving the necessary fitup between the stiff skins and the core at braze temperature. Two panels, approximately 3 by 8 ft, were successfully brazed. The first was statically tested and met the 30,000 lb/in. design requirement. Figure 3-8 is a photograph of the completed part.

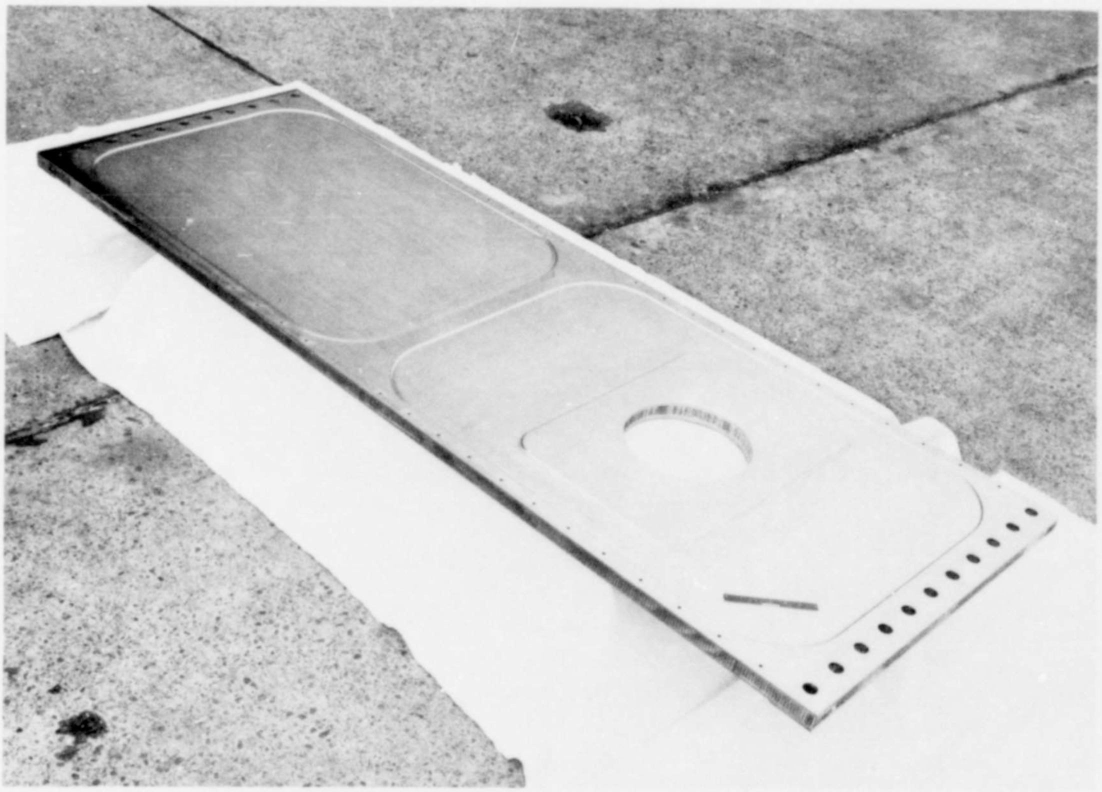


FIGURE 3-8.—COMPLETE HIGH-LOAD PANEL (30,000 POUNDS PER INCH)

3.2.3 Process/Technique Development

The large quantity of simple flat panels (the third basic objective) presented no fabrication difficulty; however, these panels plus a variety of test parts fabricated in support of the spoilers and high-load panels provide the general criteria for net size brazements as well as specific process support to the detail design requirements.

3.2.3.1 Net Braze Requirement

The fundamental requirement for net brazements was found to be the ultimate cleanliness of the retort and tooling material. To meet this requirement, it was established that the retort and tooling material has to be vacuum outgassed prior to use. In addition, it is necessary to use a vacuum pumping system which can rapidly remove the "outgassed" stop-off material and achieve a maximum retort pressure of 300 millitorr at retort blank-off.

3.2.3.2 Specific Process Development

It was found that the necessary temperature control could not be achieved on parts with large and asymmetrical masses (such as the 737 spoiler) using the original (SST) prescribed braze cycle. A modified, slower braze cycle was shown to provide the necessary control. Metallurgical analysis of braze parts showed the new cycle to be acceptable. The revised braze cycle is shown in Figure 3-9.

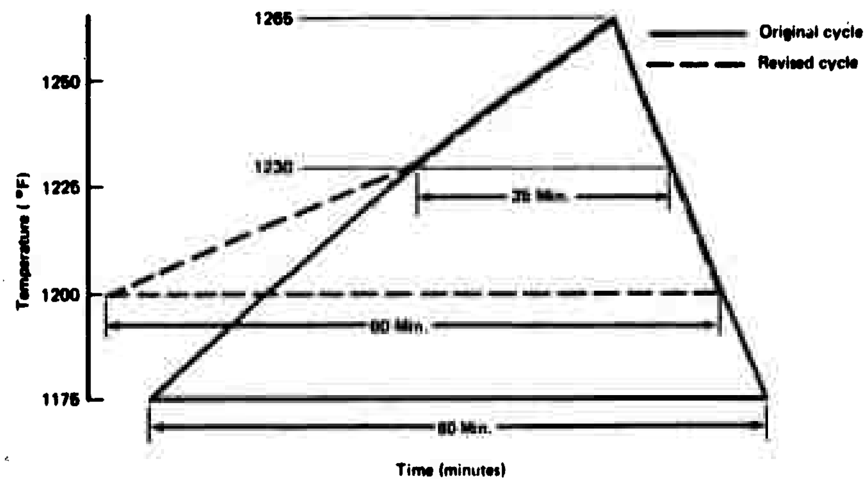


FIGURE 3-9.—BRAZE CYCLE LIMITS

Pre-braze spot welding was shown to provide the best means of controlling faying-surface braze gap. The procedure is also helpful in controlling detail alignment and fitup.

Currently available stabilizing material used for machining honeycomb core provides the necessary support to achieve the required machining quality; however, it shrinks on cooling to a degree that seriously complicates achieving the necessary part geometry control. The problem could be "worked around," but adds significantly to part cost.

3.3 MATERIAL PROPERTIES (REPORT FAA-SS-73-5-4)

The objective of this investigation was to evaluate the material properties of aluminum-brazed titanium honeycomb sandwich panels over a wide range of environmental and process variables in order to define the useful geometric and environmental limits of aluminum-brazed panels.

3.3.1 Mechanical Properties

Flatwise tension, flatwise compression, core shear, and edgewise compression tests were conducted on panels fabricated using a variety of core types, and for core depths ranging from 0.250 in. to 3.0 in. These panels were produced by production manufacturing shops per engineering process specifications. The test environment included temperatures from ambient to 1000°F and consisted of both static and sustained load stress-rupture tests.

The results have shown that aluminum-brazed titanium honeycomb sandwich panels are suitable for use under static or sustained loading conditions to 800°F, and possess static capability even to 1000°F. Figure 3-10 illustrates the effect of temperature on static mechanical properties of aluminum-brazed panels compared with the basic titanium and 3003 aluminum. As can be seen from the figure, up to approximately 400°F the strength of the brazed sandwich is equivalent to the basic titanium. For all temperatures, the brazed sandwich is much stronger than basic 3003 aluminum.

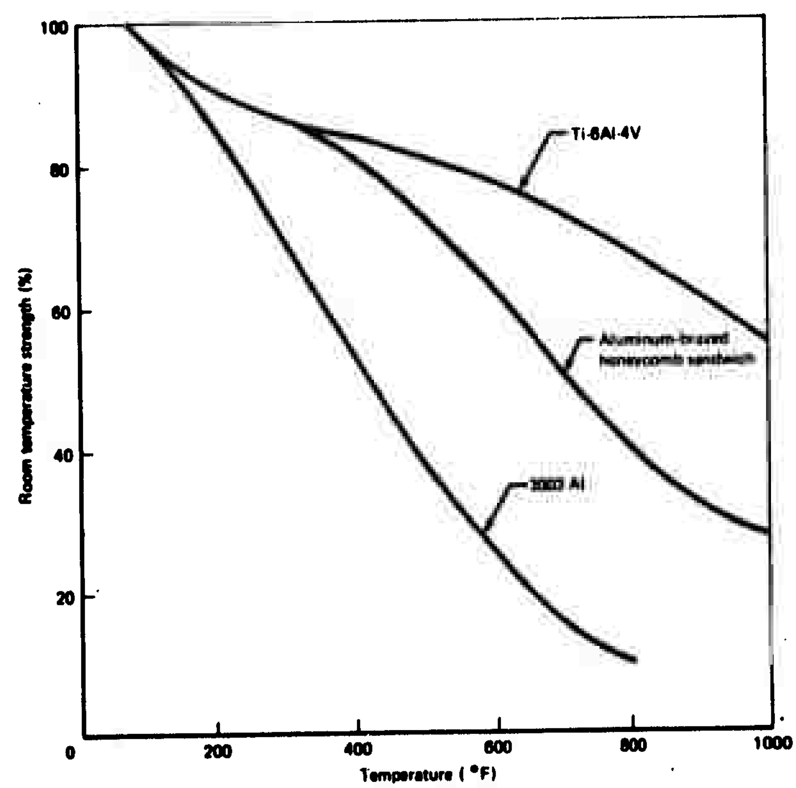


FIGURE 3-10.–EFFECT OF TEMPERATURE ON MATERIAL PROPERTIES

All mechanical properties were shown to increase with increasing core density. In addition, flatwise tensile strength was found to be influenced by core foil thickness. Core depth was found to inversely affect all mechanical properties except edgewise compression strength.

3.3.2 Thermal Conductivity

Thermal conductivity tests were conducted on aluminum-brazed titanium honeycomb sandwich panels to study the factors controlling conductivity with the objective of increasing the insulation value of brazed panels. The effects of core geometry, braze alloy, and braze node fillet size were studied. The results showed that the number of nodes/sq in. was the principal factor influencing thermal conductivity. Braze alloy and braze node fillet size were also shown to influence conductivity but their effect was secondary to node density. It was demonstrated that the thermal conductivity of aluminum-brazed panels can be reduced to 2.5 Btu-in./sq ft-hr$^{\circ}$F (equivalent to diffusion bonded honeycomb sandwich), see Figure 3-11. Thus, thermal conductivity can be tailored to design application requirements. To date, minimum thermal conductivity has only been achieved with some sacrifice in mechanical properties; however, it is believed that the loss in mechanical properties can be recovered with additional development.

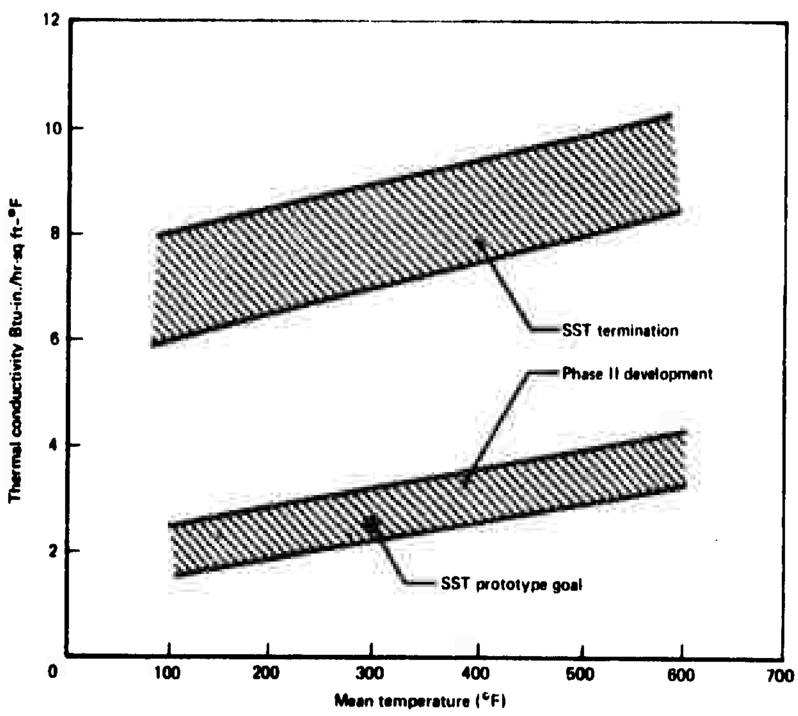


FIGURE 3-11.—THERMAL CONDUCTIVITY OF ALUMINUM-BRAZED TITANIUM SANDWICH

3.3.3 Fatigue

Aluminum-brazing was found to reduce the fatigue strength of bare, monolithic titanium. However, the result was no worse than the effect of normal manufacturing imperfections and, therefore, had little or no effect on the basic fatigue design strength of titanium.

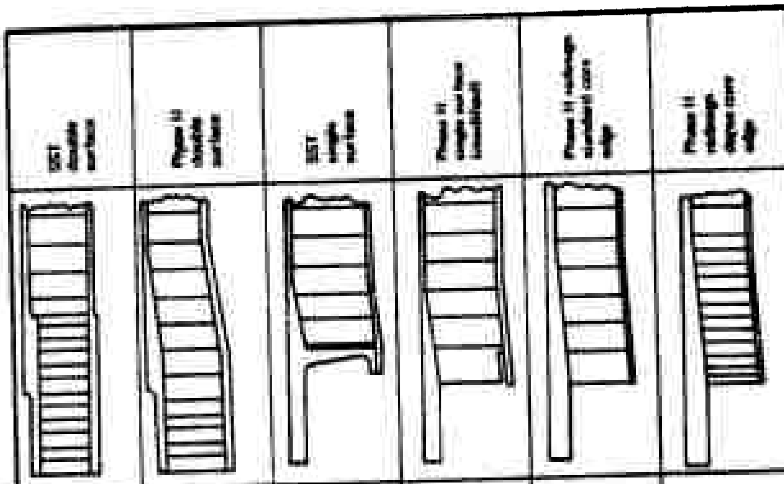
3.4 STRUCTURAL VERIFICATION (REPORT FAA-SS-73-5-5)

This program was implemented to verify the structural efficiency and reliability by testing structural components. Several structural components were available from the SST program. Additionally, several new components were fabricated on the scale-up portion of the overall Phase II program (see Vol. III, report FAA-SS-73-5-3). The evaluation of the structural properties of these components was divided into three groups: (1) joints, (2) flat panels, and (3) wedges.

3.4.1 Joints

Cost analysis studies (Vol. VII, report FAA-SS-73-5-7) showed that the SST prototype joint designs were costly to fabricate. Alternate, less expensive designs were developed and test parts fabricated for structural verification. The results of tests on SST joint designs and alternative (Phase II) designs are shown in Table 3-1. The table also depicts the principal design features. As can be seen from the results, the new designs proved to be superior in all respects.

TABLE 3-1.—COMPARISON OF JOINT PERFORMANCE FOR DIFFERENT JOINT DESIGNS



Property						
Static						
Tension, ksi	145.5	155	–	101	130	–
Compression, ksi	146	150	37	90.5	113	140.5
Fatigue (R = -.3)						
Maximum cyclic gross area stress, ksi	34	34	–	30.8	34	–
Life, cycles (log average)	126,000	417,000	–	122,000	260,000	–

3.4.2 Panels

Flat panel tests consisted of one full-scale double-surface edge panel and four small single-surface edge panels available from the SST program, plus a double-surface high-load panel produced on the Phase II program.

The SST double-surface edge panel was tested in axial compression and failed by column instability at the predicted load. The SST design single-surface edge panels did not reach design load and showed that the surface to which the load was applied took most of the load.

The second double-edge panel was fabricated on the Phase II program to demonstrate the capability of the process for heavy, highly loaded (30,000 lb/in.) structure (ref. Vol. III). The part contained an access hole designed using the braze process limitations in effect at SST termination. Namely, only one step change in panel section was allowed. This prohibited gradually tapering into the access hole reinforcement to minimize its stress concentrating effect. The part was first tested in tension to map the stress distribution around the access hole. It was then cut into two pieces and these were tested in compression. The access-hole design was demonstrated to be structurally inadequate for sustaining the 30,000 lb/in. design end load. The half without the access hole successfully exceeded the design end load.

Based on the results from the new joint configurations, it is anticipated that structurally efficient panels having access holes could be designed to sustain end loads of 30,000 lb/in. or more.

Sonic fatigue tests were conducted on two panels and the aluminum-brazing system was demonstrated to be highly resistant to this form of damage.

3.4.3 Wedges

The Phase II program included development of the processing technology for wedge-shape parts. As part of that effort, 737 airplane flight spoilers were designed and fabricated. Four parts, including one preliminary design test part (PDTP), were structurally verified. The PDTP was used to develop brazing techniques and did not satisfy quality control requirements. Nevertheless, the part was statically tested to design limit load and then fatigue tested to failure at a maximum cyclic load of 75% of design limit with $R = -0.2$. Failure occurred at an inboard hinge fitting after 74,500 cycles and led to a redesign of the center yoke.

One spoiler was fatigue tested at a maximum cyclic load of 75% design limit load with $R = -0.2$ to the goal of 300,000 cycles, with no failure detected. However, two cracks in the outer skin were found when the load pads were removed for inspection. The spoiler was then statically loaded to design limit load and tip deflection for this specimen was the same as for undamaged spoilers. Two spoilers, to be evaluated in flight service on commercial airplanes, were proof-loaded to design limit load.

Spoiler loads are based on maximum actuator output. A maximum cyclic load of 75% design limit load with $R = -0.2$ was selected as a conservative representative operational load for test. Therefore, the design is considered satisfactory. Sharp corners at the aft end of the center yoke, where the skin cracks occurred, were rounded off for future design and incorporated in one of the two spoilers to be evaluated in commercial service.

3.5 CORROSION RESISTANCE (REPORT FAA-SS-73-5-6)

An extensive program was conducted to categorize the corrosion characteristics of the system relative to a wide variety of environments. Three types of testing (field service, accelerated laboratory, and fundamental electrochemical) were used to obtain the maximum possible definition and understanding. The overall scope of the program is depicted in Table 3-2. As can be seen in the table, the majority of the long-term service tests will not be completed on this contract. It is anticipated that these tests will be continued under sponsorship of NASA-Langley Research Center.

TABLE 3-2.—CORROSION TEST SUMMARY AND SCHEDULE

Test	1/2 year	1 year	1-1/2 year	2 year	3 year	4 year	5 year	6 year	8 year
Service evaluation									
a. 727 landing gear*									
SST & Phase I series		●		●	●	●			○
Phase II series	● ▲	● △	○	○ △	○ △	○ △	○ △	○	
b. 737 flight spoilers	○ △	○ △		○ △		○ △			
c. YF-12A wing bay*		●		○	○	○	○	○	
d. Jet engine exhaust*	●	●	○	○	○	○	○	○	
	1/2 month	1 month	2 month	3 month	4 month	6 month	12 month	18 month	
Accelerated lab tests									
a. Salt spray	▲	● ▲	▲	● ▲	▲	●	●	●	
b. Alternate immersion	▲	● ▲	▲	● ▲	▲	●	●	●	
c. Acidified salt spray	▲	▲	▲	▲	▲				
d. Tidal immersion	▲	▲	● ▲	▲	● ▲		●	●	
e. Stress corrosion		● ▲	● ▲		●	●	●	●	
f. Faying-surface joints	▲	▲	▲	▲	▲	▲			
Fundamental studies									
a. Solution potential	■	■							
b. Polarization	■ ▲	■ ▲							
c. Weight loss	■	■	■		■		■		
d. Effect of pH	■ ▲	■ ▲	▲	▲	▲				
e. Crevice mechanism	■ ▲	■ ▲	▲	▲	▲	▲			

Solid figure=test completed; open figure=test in progress

● Brazed honeycomb; ■ Open-face specimen; ▲ Brazed faying-surface joint

*Specimen test kits

The overall conclusion for these tests is that aluminum-brazed titanium has a basic corrosion resistance acceptable for airplane applications. The corrosion resistance is equivalent to cast 3003 aluminum with no galvanic corrosion between the aluminum and titanium. As with all aluminum structures, it is desirable to provide additional corrosion protection by means of protective finishes.

3.5.1 Field Service Evaluation

There were three types of tests utilized in this portion of the program: (1) test samples were installed on the main landing gear of 19 model 727 airplanes operated by 9 different commercial airlines, as shown in Figure 3-12; (2) test samples were installed in jet engine test cells at Pratt & Whitney and General Electric; and (3) there were two model 737 flight spoilers installed on commercial airplanes. In the first two tests, samples were removed at periodic intervals and examined visually and metallographically for corrosion. The 737 flight spoilers will be periodically inspected in situ and will be returned to Boeing for examination and structural testing at the end of the flight service exposure.

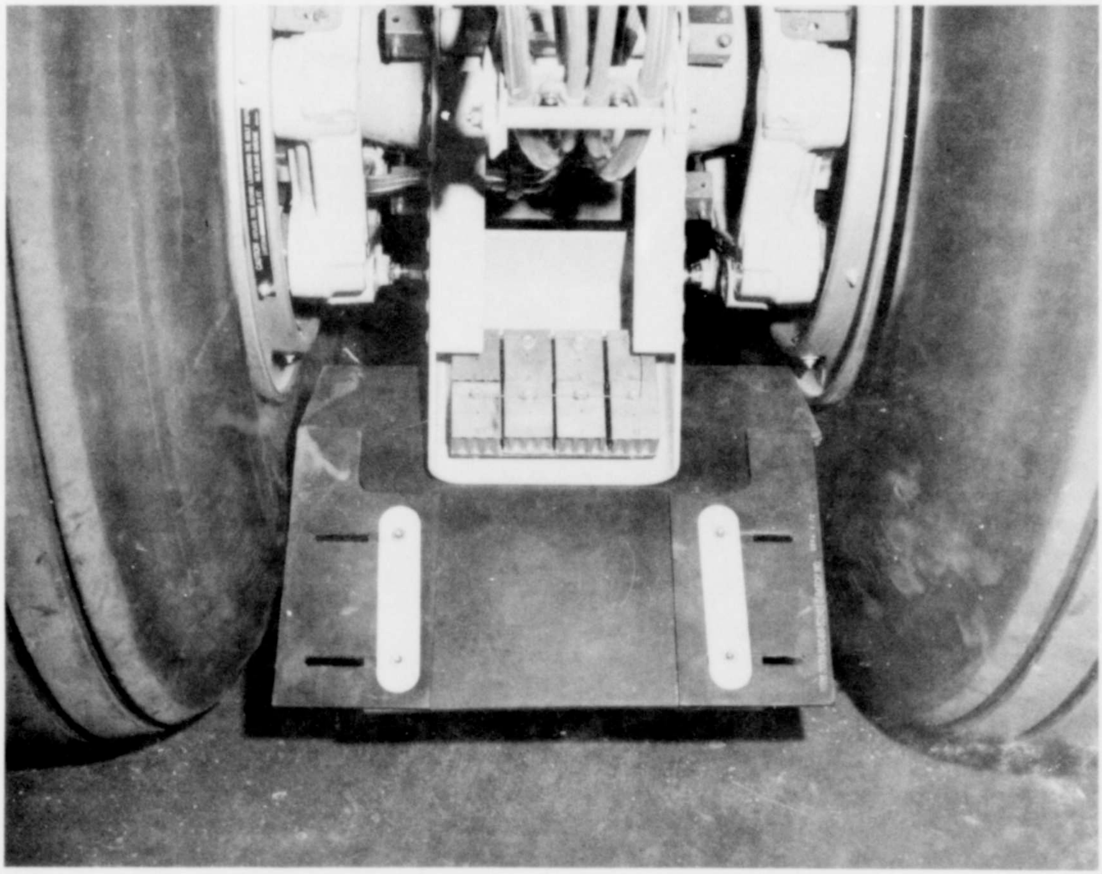


FIGURE 3-12.—LANDING GEAR CORROSION TEST INSTALLATION

With the exception of one set of specimens in a Pratt & Whitney engine test stand located on the Florida coast, none of the specimens has exhibited more than occasional superficial surface pitting corrosion. The specimens on the Florida coast showed corrosion less than halfway through the outermost fillet in 1 year.

3.5.2 Accelerated Laboratory Tests

Laboratory tests included the standard salt spray, acidified salt spray, alternate immersion, and a special outdoor test facility in which stressed and unstressed specimens were immersed in seawater approximately 50% of the time, depending on the state of the tide. Tests were conducted both stressed and unstressed. Specimens included brazed structural and acoustic honeycomb sandwich, and faying surfaces.

Several key factors were established from these tests:

1. Aluminum-brazed titanium has a corrosion resistance equivalent to 3003 aluminum alloy.
2. Corrosion at fastener holes in honeycomb sandwich is no problem, provided fasteners are installed with a maximum of 0.005-in. clearance.
3. Aluminum-brazed titanium is not susceptible to stress corrosion.
4. Faying-surface joints are permissible with appropriate design restrictions and process/fabrication control.
5. Corrosion damage is readily inspectable by nondestructive testing (NDT) methods.

3.5.3 Fundamental Studies

Fundamental electrochemical testing was conducted to achieve an understanding of the basic mechanism responsible for the corrosion behavior of the system. These studies established several factors:

1. Galvanic corrosion is *not* an active mechanism in the corrosion of aluminum-brazed titanium because the oxide films on the aluminum and titanium provide an effective barrier to the electron exchange necessary to support the oxidation-reduction reactions.
2. The oxide layers on titanium and aluminum remain intact until acid concentrations of pH 2 and pH 3, respectively, are established.
3. The naturally generated pH within a crevice does not become more acid than pH 3.2.
4. Corrosion of brazed parts occurs primarily by pitting or (in the case of faying surfaces) by crevice corrosion mechanisms.
5. The crevice corrision mechanism (in faying-surface joints) can be inhibited by maintaining a relatively thick aluminum layer in the joint and by using chromate-inhibited primer.

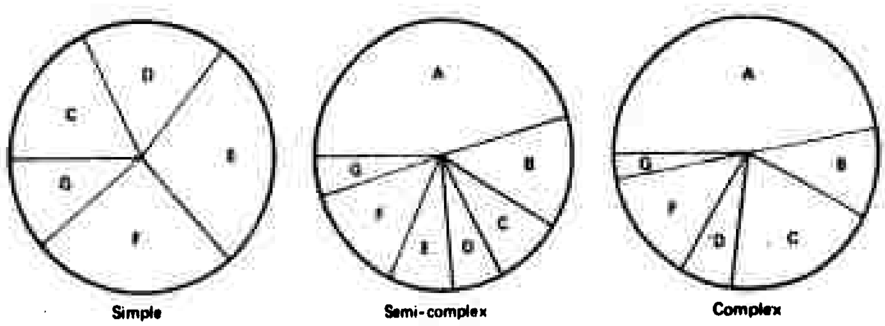
3.6 PRODUCIBILITY AND COST (REPORT FAA-SS-73-5-7)

Brazed honeycomb is the most efficient material for some types of structure. Unfortunately, it tends to be disproportionately expensive. Silver-brazed stainless steel for the B-70 (circa 1960) reportedly cost \$4000/sq ft. Aluminum-brazed titanium at the termination of the SST (1970) was estimated at \$2000/sq ft for a typical complex wing panel.

This program was instituted to analyze the costs intrinsic in the fabrication of aluminum-brazed titanium to identify the principal cost elements and, where possible, identify alternate, more cost-effective procedures. The analysis included a review of both brazing facilities and detail part fabrication. The high-cost elements were studied to identify alternate procedures which would reduce cost. In two cases, small test programs were conducted to establish the feasibility of alternatives. As a result of these studies, it is estimated that the current cost of aluminum-brazed titanium in production would be approximately \$475/sq ft for a wing panel equivalent to that proposed for the SST.

3.6.1 Preliminary Cost Analysis

A preliminary analysis was made of the cost elements involved in three flat panels of arbitrarily defined complexity, dependent on the amount of sculpturing and core splicing required. The results were plotted on pie charts, as depicted in Figure 3-13. (Items contributing less than 5% are grouped in miscellaneous.) This analysis identified four basic high-cost elements: (1) detail machining, (2) core splicing, (3) layup, and (4) NDT. Of these, detail machining was the most significant.



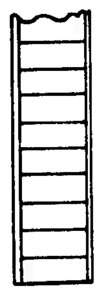
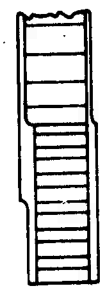
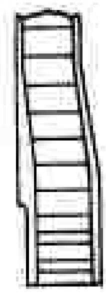
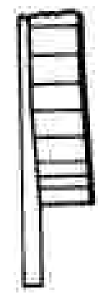
A–Machining and flattening
B–Core splicing
C–Layup
D–Weld retort and leak check
E–Braze
F–NDT
G–Miscellaneous

FIGURE 3-13.—PRINCIPAL COST ELEMENTS FROM PRELIMINARY COST STUDY

3.6.2 Detail Cost Analysis

A second analysis was conducted to obtain a refined assessment of the cost factors involved in typical aircraft structures, including wing or tail skins, internal structure, aerodynamic wedges, and nacelle components. The analysis included alternate design configurations designed to minimize detail machining. Table 3-3 illustrates a typical comparative study with costs represented as a percentage of the simple baseline panel.

TABLE 3-3.–RELATIVE COST FACTORS FOR ALTERNATE DESIGN CONCEPTS (% OF BASELINE TOTAL)

	Baseline	SST	Alternate 1	Alternate 2
Design concept				
Relative cost	1.0	3.1	2.3	2.0
Fabrication effort, %	100	100	100	100
Skin fabrication				
Machining		19.2	17.3	10.8
Other	2.4	1.6	2.2	2.5
Core blanket assembly				
Splice	1.5	17.4	21.6	23.0
Machine	33.1	23.0	14.3	16.8
Other	3.0	2.7	3.6	1.5
Braze operations				
Clean	6.5	3.1	3.5	4.8
Trim braze alloy and layup	3.8	9.4	6.5	4.5
Weld retort and leak check	8.0	2.6	3.5	4.1
Braze	8.5	2.8	3.7	4.3
Nondestructive testing	26.1	15.2	19.7	22.9
Miscellaneous	7.1	3.0	4.1	4.8

This assessment confirmed the basic findings of the initial analysis and further delineated the relative significance for different types of structure. The analysis also demonstrated large cost reductions to be realized by close attention to design detail. Additional significant cost factors, such as welding, were identified for some types of structure.

3.6.3 Cost Reduction Concepts

Each of the four basic high cost elements (detail machining, core splicing, layup, and NDT) were studied to identify conceptual, cost-saving alternatives.

- Detail Machining–Detail design concepts were generated which reduced machining costs over 50%. Feasibility hardware tests (reported in detail in Vols. III and V) showed that the saving could be achieved without significant loss in structural efficiency. If core fabrication machines could be refined sufficiently to permit fabrication to net thickness using precision slit ribbon, considerable cost saving could be achieved by elimination of the necessity of machining to remove ribbon mismatch in raw core.

- o Core Splicing—The most expensive aspect herein is splicing dense (2-xx) core to lower density (4-xx, 6-xx, etc.) core. If one ribbon of the lower density core could be attached to the 2-xx core by the core manufacturer, considerable cost savings should be attainable.

- o Layup—No direct cost-saving procedures could be identified; however, the alternative designs to minimize machining also significantly reduce layup costs.

- o NDT—Preliminary feasibility tests indicate that an automated eddy-current system could provide the necessary acceptance data at a significantly reduced cost compared to existing pulse-echo ultrasonic techniques.

3.6.4 Facilities

A comparative review of a variety of brazing heat sources and techniques was made to serve as a baseline guide for the acquisition of new capabilities.

3.6.5 Design Criteria

Three primary considerations affecting costs which a designer must consider are: (1) edge attachment method, (2) core configuration, and (3) contour.

Edge attachment through a single surface should be used wherever possible. Core configurations should be designed to minimize core splicing, particularly at angles to the core ribbon direction. Contour must, of course, fit the application but minimizing the contour in a given part may permit significant cost savings. Severely contoured parts should be designed for rotational brazing.

3.7 PROCESS SPECIFICATION (REPORT FAA-SS-73-5-8)

The process specification and engineering acceptance criteria contained in Vol. VIII are the basic requirements established at the end of the SST program. The data contained in the several technical reports can be used to update the requirements of the specifications.

GLOSSARY

alloy migration	non-uniform flow of braze alloy
aluminide	$TiAl_3$ intermetallic compound
blank-off	isolation of the braze retort from the vacuum pumping system and the inert gas system
brazement	an assembly whose component parts are joined by brazing
capillary	very close space between two solid surfaces
cruciform	a cross-shaped fitting for the introduction of point loads
exothermic	chemical reaction which generates heat
faying surfaces	two surfaces in close proximity
fusion, heat of	heat energy required to convert solid metal to liquid metal
galvanic corrosion	corrosion associated with the current of a galvanic cell consisting of two dissimilar metals in contact in the presence of an electrolyte
microprobe	an electron beam instrument for quantitative or qualitative microscopic chemical analysis
net braze	brazing to final geometry
node	contact surface between adjacent core ribbons forming the capillary
purge	evacuation and inert-gas back-filling of a retort for the purpose of developing a controlled atmosphere for brazing
retort	a metal vessel used to contain a controlled atmosphere during brazing operations
scale-up	the process of translating laboratory techniques to manufacturing procedures
septum	one or more internal sheets separating honeycomb blankets of a multilayer honeycomb sandwich panel
slip sheet	a loose sheet of material placed between the retort tooling and the part during brazing operations
torr	a unit of vacuum measurement (1 mm Hg)